

Mapping Between the CIMSteel Integration Standards and Industry Foundation Classes Product Models for Structural Steel

By

Mr. Robert R. Lipman
National Institute of Standards and Technology
Building Environment Division
Gaithersburg, Maryland

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MAPPING BETWEEN THE CIMSTEEL INTEGRATION STANDARDS AND INDUSTRY FOUNDATION CLASSES PRODUCT MODELS FOR STRUCTURAL STEEL

Robert R. Lipman¹

ABSTRACT

The CIMsteel Integration Standards (CIS/2) are the product model and electronic data exchange format for structural steel project information. CIS/2 is intended to create a seamless and integrated flow of information among all parties of the steel supply chain involved in the construction of steel framed structures. The Industry Foundation Classes (IFC) are the product model developed by the International Alliance for Interoperability to facilitate interoperability in the building industry. The recent interest in Building Information Modeling in the AEC community has shown there is a need for a mapping between the CIS/2 and IFC product models. While the CIS/2 and IFC product models have different views of modeling structural steel, a useful mapping between the two product models was developed. The mapping will permit structural steel models from CIS/2-aware design, analysis, detailing and fabrication software packages to be imported into IFC-aware software packages to do model coordination between the structural steel and the other parts of the building such as floors, walls, windows, doors, and HVAC systems. The mapping has been implemented as a CIS/2 to IFC file translator. IFC files generated from CIS/2 have successfully been imported into many IFC-aware software applications including several of the major CAD applications used in the AEC industry.

KEY WORDS

harmonization, interoperability, product model, structural steel, IFC, CIS/2.

INTRODUCTION

A recent NIST study concluded that there was at least \$15.8 billion lost in 2004 due to inadequate interoperability in the commercial, institutional, and industrial facilities industries (Gallaher et al. 2004). Two-thirds of the costs are borne by owner-operators, which incur these costs mostly during ongoing facility operations and maintenance. During the design life-cycle phase, architects and engineers incurred almost \$1 billion in interoperability costs. Of that \$463 million were for the cost of manually reentering information. Standardized

¹ Research Engineer, Building and Fire Research Laboratory, NIST, 100 Bureau Drive, Stop 8630, Gaithersburg, MD, 20899-8630, USA, Phone 301/975-3829, FAX 301/975-5433, robert.lipman@nist.gov

information representations and formats, such as product models, properly implemented in CAD software can play an important part in mitigating some of those costs.

Interoperability is a major component in the recent emphasis on building information models and modeling (BIM) in the architecture, engineering, and construction (AEC) industry. Using BIM does not mean that there will be one software package that contains the entire model and that will perform all functions. Rather a construction project will require a suite of software packages that will need product models to be exchanged between them.

In the steel construction industry, product models now have legal standing rather than traditional 2D drawings if not explicitly stated in the construction contract. The recently added Appendix A to the American Institute of Steel Construction's (AISC) Code of Standard Practice states that the model shall "govern over all other forms of information, including drawings, sketches, etc." The concrete and architecture industries are looking to the steel industry for guidance as to how to implement a similar code of practice.

The International Alliance for Interoperability (IAI) has initiated a CIS/2 – IFC harmonization project to facilitate interoperability between the two product models. The benefits of the project include faster design and development of steel structures by architects, faster start-up of steel fabrication, improved coordination between steel design and fabrication with other building systems such as windows, walls, floors, doors, cladding, HVAC, and MEP systems. Typically models generated in CIS/2 compatible structural steel software have not been interoperable with IFC compatible CAD software used in the AEC industry. The harmonization project is reviewing the IFC schema and extensions for possible modifications and additions to make it more interoperable with CIS/2.

This paper describes research at NIST for a mapping between the CIS/2 and IFC product models and a software program for translating CIS/2 files to IFC files.

NOTATION AND SCOPE

In a CIS/2 or IFC file entity names are always in upper case letters such as SECTION_PROFILE or IFCBEAM. In this paper, to differentiate between entities from each type of file and to improve readability, CIS/2 entities will be written as Section_profile and IFC entities will be written as IfcBeam. Similar entities that can be grouped together will be written as Ifc{Beam/Column/Member} or Section_profile_{I/T}_type.

The CIS/2 specification covers a wide variety of features of structural steel. Details such as the shape and dimensions of groove and fillet welds can be specified. In practice, software packages have implemented only the parts of CIS/2 specific to their functionality. There are parts of the CIS/2 standard that have never been implemented by any software package. The details about welds are just one example. References in this paper to the capabilities of CIS/2 are based on what has been implemented in practice.

CIS/2 PRODUCT MODEL

The CIMsteel Integration Standards (CIS/2) (Crowley and Watson 2000, Eastman et al. 2005, <http://www.cis2.org/>) is the product model for structural steel project information and is intended to create a seamless and integrated flow of information among all parties of the steel supply chain involved in the construction of steel framed structures. It has been adopted

by AISC as their format for Electronic Data Interchange (EDI) and has been implemented by many structural steel analysis, design, detailing, and fabrication software packages. CIS/2 is the result of the pan-European Eureka EU130 CIMsteel Project.

The technical basis for representing CIS/2 information is STEP (ISO 10303:1992). The CIS/2 schema is defined using the STEP Part 11 EXPRESS language. STEP Part 21 is used for representing a CIS/2 product model in a physical file. CIS/2 also borrows from STEP Part 42 for basic representations of geometry such as coordinate systems, points, curves, and surfaces. These aspects of the CIS/2 information schema are very similar to the IFC product model information schema. This commonality facilitates the mapping between the two product models.

There are three views of structural steel in CIS/2, an analysis model, a design model, and a detailed model. The analysis model is a finite element model representation including nodes, element connectivity, section profiles, loads, load cases, material properties, and analysis results such as displacements, and reaction forces. Analysis models generally do not contain details about connections or non-load bearing material such as handrails and decking.

A design model is a physical representation of a steel structure and can contain material such as clip angles, gusset plates, handrails, decking, and stairs. A design model does not contain connection information such as bolts, holes, and welds. However, a design model can have an association between parts that are connected to each other without specifying the connection type such as bolted or welded, although it can indicate if the connection is pinned or rigid. Prismatic parts in the design model are specified by a section profile and a length. Plates are specified by a thickness and points defining the perimeter. The position and orientation of the parts, relative to a global coordinate system, are specified by an origin and two vectors, one for the longitudinal axis and the other for the up-direction of the part. Typically a design model contains no assemblies or groupings of parts.

A detailed model, also known as a physical, manufacturing, or fabrication model, is usually a model that includes bolts, holes, and welds and miscellaneous materials such as decking, handrails, and grating. Fabrication information is frequently generated from the detailed model. The dimensions of prismatic parts and plates are specified in the same manner as in a design model. Parts are grouped in assemblies normally consisting of a main member, such as one beam or column, and the associated clip angles, gusset plates, stiffeners, and other smaller connection material. The location of a part is specified similar to a design part; however, it is always relative to its parent assembly. Assemblies are then located in the global coordinate system. Individual assemblies can be grouped into larger assemblies such as trusses; however, this is not usually done in a CIS/2 model. Assemblies can also be grouped into zones that can indicate a construction sequence. The collection of all assemblies represents the complete structure. Bolts and welds, known as joint systems, are located relative to an assembly. Holes are located relative to a part. A pattern of bolts or holes is specified with a layout in a 2D plane.

In CIS/2, there is a logical relationship between all three models. Analysis model elements can be associated with design parts in a design model or located parts in a detailed model. For example, a beam that is subdivided into several small ones in an analysis model is logically only one physical beam in a design or detailed model. This association provides a many-to-one relationship.

Figure 1 shows a sample of a column in an assembly from a detailed model. The order of the entity instances has been changed from the original file and indentation added to show the hierarchy and relationship between the various entities.

```
#2486= LOCATED_PART(5402,'w10',$,#1601,#443,#4027);
#1601= (COORD_SYSTEM('','Part CS',$,3)COORD_SYSTEM_CARTESIAN_3D(#3624)
      COORD_SYSTEM_CHILD(#3990));
#3624= AXIS2_PLACEMENT_3D('Part CS',#2706,#3536,#3533);
#2706= CARTESIAN_POINT('axis2_placement_3d point',(25.4,0.,0.));
#3536= DIRECTION('local z',(0.,0.,1.));
#3533= DIRECTION('local x',(1.,0.,0.));
#3990= COORD_SYSTEM_CARTESIAN_3D('Global','Assembly CS',$,3,#3618);
#3618= AXIS2_PLACEMENT_3D('Assembly CS',#2684,#3532,#3531);
#2684= CARTESIAN_POINT('axis2_placement_3d point',(0.,0.,0.));
#3532= DIRECTION('local z',(-1.,0.,0.));
#3531= DIRECTION('local x',(0.,0.,1.));
#443= (PART(.ROLLED,$)PART_PRISMATIC()PART_PRISMATIC_SIMPLE(#438,#1514,$,$)
#438= SECTION_PROFILE(0,'W27x194',$,$,5,.T.);
#1514=POSITIVE_LENGTH_MEASURE_WITH_UNIT
      (POSITIVE_LENGTH_MEASURE(7899.4),#1504);
#1504=(LENGTH_UNIT()NAMED_UNIT(*)SI_UNIT(.MILLI.,.METRE.));
#4027= LOCATED_ASSEMBLY(1,'C_5[1]','column',#3990,$,#2657,#4097);
#3990= COORD_SYSTEM_CARTESIAN_3D('Global','Assembly CS',$,3,#3618);
#2657= ASSEMBLY_MANUFACTURING(0,'C_5','column',$,0,.LOW.,$,$,$,$);
#4097= STRUCTURE(0,'Structure',$);
```

Figure 1: Located Part in a CIS/2 file of a Detailed Model

The top-level entity is a Located_part (#2486) that associates a Part (#443) with a Coord_system (#1601). The Located_part also refers to a Located_assembly (#4027). The Part refers to a Section_profile (#438) and a Length (#1514). The Located_assembly also refers to a Coord_system (#3990), an Assembly (#2657), and a Structure (#4097). The Section_profile entity does not refer to any dimensions of the W27x194 section. Without the dimensions an application reading this file would use a lookup table of section dimensions. Sections with explicit dimensions for the depth, width, and thicknesses can be specified with Section_profile{I_type/T_type/Channel/Angle} and others.

These statements describe a physical part (W27x194 wide-flange section) and its instantiation as a located part that has a location in an assembly that in turn is located in the structure. All located parts must be unique; however, there can be multiple references to a part. An individual part can have multiple occurrences or instances, with multiple references to the Part (#443) by other Located_part entities. There is no entity that groups together all parts in an assembly. Located_assembly does not list all of its member parts.

In a design model, Design_part is used instead of Located_part and there is no Located_assembly. To model plates in a design or detailed model, Part_sheet_bounded is used instead of Part_prismatic. Cutouts such as miter cuts, notches and chamfers are modeled with Feature_volume_prismatic which parametrically specifies the type, dimensions, and position. Cutouts are located on parts with Located_feature_for_located_part. Analysis model elements are not located as in a design or

detailed model. Their position and orientation is specified by the coordinates of starting and ending nodes.

IFC PRODUCT MODEL

The Industry Foundation Classes (IFC) are the product data model developed by the IAI (<http://www.iai-international.org/>) to facilitate interoperability in the building industry. The first version of the standard (IFC1.0) was released in 1997 and covered basic architectural elements such as wall, floors, doors, windows, beams, and columns. Over time, the IFC standard has evolved and expanded through several versions (IFC2.0, IFC2x, IFC2x2) and the recently released IFC2x3. New versions of the standard have expanded into other domains including building services (HVAC, plumbing, electrical), facilities management (cost models, permitting, service life data, operations, maintenance), architectural extensions (stories, spaces, 2D drawings), and structural (analysis model, steel, reinforced concrete).

In IFC there are two views of structural steel, an analysis model and a physical model. The analysis model is very similar to the CIS/2 analysis model. The analysis model also provides for a mapping between an analysis element and a physical representation although it is only a one-to-one relationship. The IFC physical model does not differentiate between a design and detailed model. There is no requirement that parts be grouped into assemblies. Bolts, holes, and welds can be modeled; however, there is no way to specify a 2D layout of them.

Figure 2 shows a column in an assembly from an IFC file that corresponds to the sample CIS/2 file in Figure 1. Some of the entity ids in the IFC file are the same as in the CIS/2 file to show the relationship between the entities. The top-level entity is an `IfcColumn` (#2486) that associates an `IfcProductDefinitionShape` (#5201) with an `IfcLocalPlacement` (#1601) that refers to another `IfcLocalPlacement` (#3990). The two `IfcLocalPlacement` correspond to the coordinate transformations for the `Located_part` and `Located_assembly` in the CIS/2 file. However, there is no indication that it is actually an assembly. In IFC parts can be grouped into assemblies with `IfcElementAssembly` and `IfcRelAggregates` although it does not convey the sense that a part is located relative to an assembly.

All products, such as the `IfcColumn`, have a product representation. `IfcProductDefinitionShape` (#5201) refers to an `IfcShapeRepresentation` (#5202) that defines the product geometry. The `IfcProductDefinitionShape` is the type of product and the occurrence is an `IfcColumn`. A more formal method to specify the type is to use `IfcColumnType` which would refer to the `IfcProductDefinitionShape` through `IfcRepresentationMap`. In IFC2x2, multiple occurrences can refer to the same product. However, in IFC2x3 a mapped representation using `IfcMappedItem` must be used to reuse a product representation.

The shape representation is an `IfcExtrudedAreaSolid` (#5203) which refers to a parameterized profile `IfcIShapeProfileDef` (#438). The `IfcIShapeProfileDef` corresponds to the `Section_profile` in the CIS/2 file. Parameterized profiles always refer to their section depth, width, and thickness. Other parameterized profiles that specify section dimensions are `Ifc{I/T/U/L/C/Z/Rectangle/Circle}ShapeProfileDef`. The section profile can also be specified by an arbitrary bounded curve with `IfcArbitraryClosedProfileDef`. Instead of an extruded solid, the shape representation can also be an `IfcFacetBrep`, known as a faceted

boundary representation (B-rep). Multiple shape representations are allowed in IFC where typically the second representation is a simpler geometry such as a bounding box.

```
#2486= IFCCOLUMN('0n6KP7eKgJIPWskOQE8n00',#100005,'w10',$,$,#1601,#5201,$);
#100005= IFCOWNERHISTORY(#100003,#100004,$,.ADDED.,$,$,$,1138918188);
#1601= IFCLOCALPLACEMENT(#3990,#3624);
#3990= IFCLOCALPLACEMENT($,#3618);
#3618= IFCAXIS2PLACEMENT3D(#2684,#3532,#3531);
#2684= IFCCARTESIANPOINT((0.,0.,0.));
#3532= IFCDIRECTION((-1.,0.,0.));
#3531= IFCDIRECTION((0.,0.,1.));
#3624= IFCAXIS2PLACEMENT3D(#2706,#3536,#3533);
#2706= IFCCARTESIANPOINT((25.4,0.,0.));
#3536= IFCDIRECTION((0.,0.,1.));
#3533= IFCDIRECTION((1.,0.,0.));
#5201= IFCPRODUCTDEFINITIONSHAPE('w10 Column',$,(#5202));
#5202= IFCSHAPEREPRESENTATION(#100011,'Body','SweptSolid',(#5203));
#100011= IFCGEOMETRICREPRESENTATIONCONTEXT('Plan','Design',
3,1.0E-5,#100040,$);
#100040= IFCAXIS2PLACEMENT3D(#100041,#100044,#100042);
#100041= IFCCARTESIANPOINT((0.,0.,0.));
#100044= IFCDIRECTION((0.,0.,1.));
#100042= IFCDIRECTION((1.,0.,0.));
#5203= IFCEXTRUDEDAREASOLID(#438,#100049,#100044,7899.4);
#438= IFCISHAPEPROFILEDEF(.AREA.,'W27X194',#100050,
356.5,714.0,19.1,34.0,$);
#100050= IFCAXIS2PLACEMENT2D(#100051,#100052);
#100051= IFCCARTESIANPOINT((0.,0.));
#100052= IFCDIRECTION((1.,0.));
#100049= IFCAXIS2PLACEMENT3D(#100041,#100042,#100043);
#100041= IFCCARTESIANPOINT((0.,0.,0.));
#100042= IFCDIRECTION((1.,0.,0.));
#100043= IFCDIRECTION((0.,1.,0.));
#100044= IFCDIRECTION((0.,0.,1.));
```

Figure 2: Column in an IFC file

MAPPING BETWEEN CIS/2 AND IFC

Table 1 shows a partial list of CIS/2 entities related to analysis, design, and detailed models that can be mapped directly to corresponding IFC entities. The mapping between CIS/2 and IFC for an analysis model is straightforward and there is a one-to-one correspondence between entities. The exception, however, for IFC analysis models is that they also have an `IfcProductRepresentation` associated with the `IfcStructuralCurveMember` consisting of an `IfcTopologyRepresentation`, `IfcEdge`, and `IfcVertexPoint`.

The mapping between CIS/2 and IFC for design and detailed models is not as clear-cut and is more of a one-to-many mapping. For example, in CIS/2 a Part is effectively an extruded solid defined by a `Section_profile` and a length where the extrusion direction is the local X axis. However, in IFC, the equivalent `IfcProductDefinitionShape` can be either one of two types of extruded shape profiles (parameterized or arbitrary) or a B-rep. The most compact shape representation that also retains the intent from the CIS/2 model is the parameterized profile; however, some applications that import IFC files have not completely

implemented this type of shape representation. The other shape representations do not have the parametric depth, width, and web and flange thicknesses information for structural steel shapes. Without the parametric information an importing IFC application could not distinguish between an I-beam and a channel section. One possible solution is to create an IfcPropertySet that contains the dimensions of the section and associate it with the shape representation.

Table 1: A Representative Sample of the CIS/2 to IFC Entity Mapping

CIS/2 Entity	IFC Entity
Analysis_model	IfcStructuralAnalysisModel
Analysis_result_{node/element_node}	IfcStructuralPointReaction
Analysis_result_set	IfcStructuralResultGroup
Applied_load_static_force	IfcStructuralLoadSingleForce
Assembly_map	IfcRelAssignsToProduct
Axis2_placement_3d	IfcAxis2Placement3D
Boundary_condition_logical	IfcBoundaryNodeCondition
Cartesian_point	IfcCartesianPoint
Context_dependent_unit	IfcConversionBasedUnit
Coord_system_cartesian_3d	IfcLocalPlacement
Design_part	Ifc{Beam/Column/Member/Plate}
Element_curve_simple	IfcStructuralCurveMember
Element_node_connectivity	IfcRelConnectsStructuralMember
Fastener_simple_bolt	IfcProductDefinitionShape
Joint_system_mechanical	IfcMechanicalFastener
Joint_system_welded	IfcFastener
Load_case	IfcStructuralLoadGroup
Load_element_distributed_curve_line	IfcStructuralLinearAction
Load_node	IfcStructuralPointAction
Loading_combination	IfcStructuralLoadGroup
Located_assembly	Ifc{Group/ElementAssembly}
Located_joint_system	Ifc{Group/BuildingElementProxy}
Located_part	Ifc{Beam/Column/Member/Plate}
Node	IfcStructuralConnectionPoint
Part	IfcProductDefinitionShape
Reaction_{displacement/force}	IfcStructuralLoadSingle{Displacement/Force}
Release_logical	IfcBoundaryNodeCondition
Section_profile_{angle/channel}	Ifc{L/U}ShapeProfileDef
Section_profile_{circle/rectangle}	Ifc{Circle/Rectangle}ShapeProfileDef
Section_profile_compound	IfcCompositeProfileDef
Section_profile_{i/t}_type	Ifc{I/T}ShapeProfileDef
Si_unit	IfcSIUnit
Zone_of_structure	IfcGroup

According to the IFC specifications an `IfcColumn` is a vertical, or nearly, vertical structural member that is not required to be load bearing. Similarly an `IfcBeam` is a horizontal member. An `IfcMember` is defined as a structural member that carries loads between or beyond points of support and is intended for bracing and other similar members. An `IfcPlate` is a flat part with constant thickness. Structural parts can be classified as `Ifc{Beam/Column/Member}` based on the direction of its longitudinal axis. However, there are several cases where that classification is not obvious. Consider a horizontal assembly consisting of a beam and associated connection material such as clip angles and gusset plates. The longitudinal axis of the beam is horizontal while the longitudinal axis of the clip angles is vertical. Should the clip angles be an `IfcColumn` although it is part of a horizontal beam assembly? Similarly, should the gusset plates be an `IfcPlate`? Should all of the parts be `IfcBeam` because the entire assembly is a beam? It is not clear what the right solution is and might depend on how an IFC importing application handles the semantic difference between parts. Consider also miscellaneous material such as handrails, decking, grating, and purlins. Should there be another classification for this type of material or is `Ifc{Beam/Column/Member/Plate}` sufficient?

Cutouts in a CIS/2 model such as miter cuts, square notches, and angled chamfers are modeled parametrically. Those parameters include the length and depth of a notch or chamfer, the angle of a miter cut and position of the cutout (start or end face, top or bottom edge, left or right edge). In IFC there is no way to parametrically describe cutouts although it is being considered for a future release. General-purpose boolean operations can be applied to the shape representation with `IfcBooleanResult` and `IfcBooleanClippingResult`, the later being used for miter cuts and chamfers and the former for notches. The `IfcBooleanClippingResult` uses an `IfcHalfSpaceSolid` and properly located `IfcPlane` and can only be applied to extruded solids. Most IFC importing applications have not implemented `IfcBooleanResult`; therefore notches can only be model with a B-rep shape representation. Regardless of the shape representation used and how the cutouts are applied to the shape, the parametric fabrication intent of the cutouts is lost. It would be difficult for an IFC importing application to determine from a B-rep the dimensions and position of a notch on an I-beam. `IfcPropertySet` can be used to capture the parameters of a cutout although the cutout properties might not be used by an IFC importing application.

A 2D pattern of bolts in a CIS/2 model is described by a `Joint_system_mechanical` entity that refers to the cartesian coordinates of the bolts relative to the location of the joint system in its parent assembly. There is no equivalent way to model bolts in IFC although it is being considered for a future release. Bolts and other fasteners such as nails use `IfcMechanicalFastener` which is a product just like any other `Ifc{Beam/Column}`. Its shape representation is made up of two extruded solids, one for the head of the bolt and one for the shank. There is no way in IFC to create the pattern of bolts; therefore `IfcLocalPlacement` is used to locate each individual `IfcMechanicalFastener`.

The CIS/2 model in Figure 1 refers to two coordinate systems for locating the part and the assembly. The same two coordinate systems are used in the IFC model in Figure 2; however, there are three other coordinate systems in the IFC model. The first is related to the `IfcGeometricRepresentationContext` which defines the default coordinate system. The other two are related to the coordinate system in which the `IfcExtrudedAreaSolid` and

IfcIShapeProfileDef are defined. These define the coordinate system and direction of the extrusion. There is no constraint on what the extrusion direction is in IFC while in CIS/2 it is always the local X axis.

IMPLEMENTATION

The CIS/2 to IFC mapping has been implemented as a free software program available from NIST at <http://cic.nist.gov/vrml/cis2.html>. The translator between CIS/2 and IFC was developed as part of the existing CIS/2 to VRML (Virtual Reality Modeling Language) translator (Lipman and Reed, 2003). Figure 3 show the user interface from the translator and the options available for generating IFC files. These options allow the generation of IFC files with many of the different representations described in this paper. The CIS/2 to IFC translator has been tested with over 500 different CIS/2 files for most combinations of shape and element representations, using mapped and non-mapped representation, and for the IFC2x, IFC2x2, and IFC2x3 schemas. All of the IFC files were tested with Express Engine (<http://exp-engine.sourceforge.net>) which checks for conformance to the schema. Some of the IFC files were tested in a variety of IFC viewers, model checkers, and CAD applications that import IFC files. This served to show the capabilities and limitations of those programs.

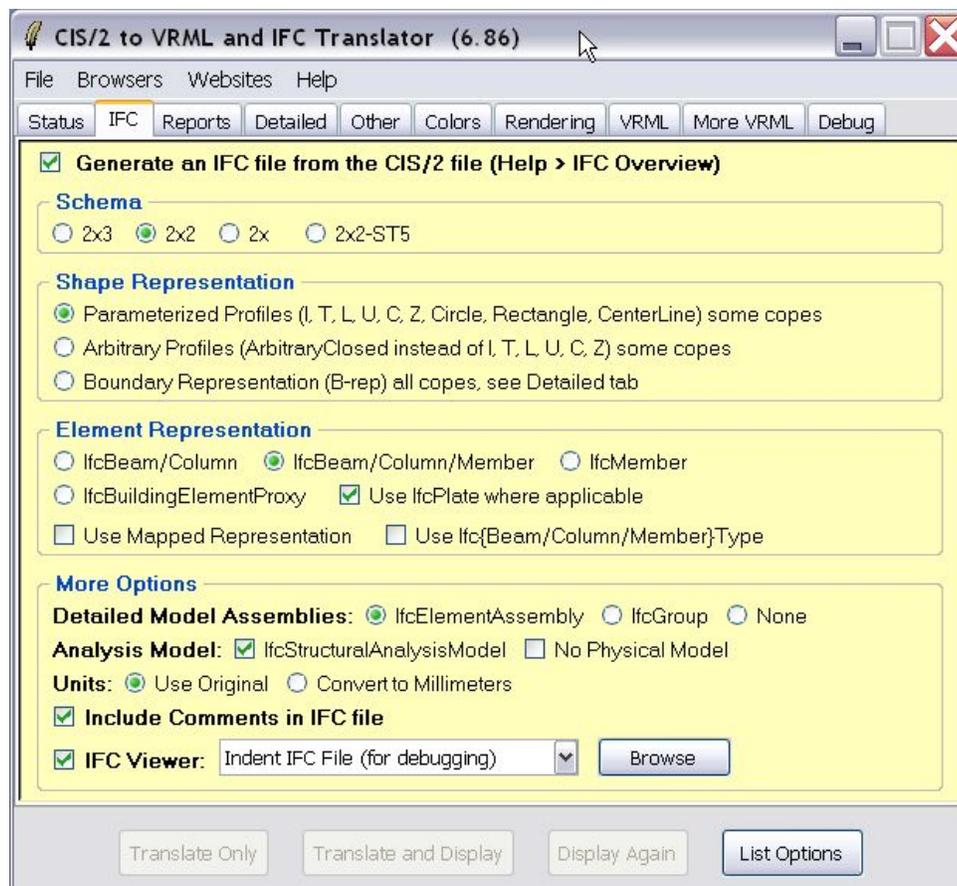


Figure 3: IFC options in the CIS/2 to VRML and IFC Translator

CONCLUSIONS

A mapping between the CIS/2 and IFC product models for structural steel has been developed and has been implemented in the form a CIS/2 to IFC translator. While CIS/2 is straightforward in its definitions of analysis, design, and detailed models, some of that information is lost when mapping to IFC. The multiple methods of representing structural steel in an IFC file needs to be clarified. For example, parameterized profiles `Ifc{I/T/L/U/C/Z/Rectangle/Circle}` should always be used for structural steel. A method for defining a 2D pattern of bolts and holes needs to be implemented in IFC. Recommended practices for generating IFC files for structural steel need to be developed. For example, classifying a member as `Ifc{Beam/Column/Member/Plate}` needs to be made clear for parts in an assembly. When using `IfcExtrudedAreaSolid`, an agreed upon extrusion direction needs to be decided upon. Many of these possible recommended practices are also needed to facilitate an IFC to CIS/2 mapping. Without defining a view of structural steel in IFC it will be difficult to map the multiple IFC representations to a single representation in CIS/2. This is also important when trying to roundtrip an IFC file. For example, an IFC file, using a parameterized profile shape representation, imported into an IFC-aware CAD application and then exported back out might use a different shape representation. Without the same shape representation it would be difficult to map the IFC file back to a CIS/2 representation.

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